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Dear Harold,

Enclosed is an advance copy of the final report for contract # F49620-95-1-0027 entitled "Studies of High- $T_c$  Superconducting Films for High-Power Microwave Applications." This is for your information. At the same time another copy has been started through the bureaucracy of MIT to send the right number of copies and with the proper transmittal letters etc.

Sincerely

A handwritten signature in black ink, appearing to read "Dan Oates", with a stylized flourish at the end.

Dan Oates

# **Studies of High- $T_c$ Superconducting Films for High-Power Microwave Applications**

AFOSR Grant/Contract # F49620-95-1-0027

Final Report

15 Oct 94 – 15 Oct 97

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## **OBJECTIVES**

- Measurement and modeling of the nonlinear microwave properties of thin films of high- $T_c$  materials in order to understand the loss mechanisms and the nonlinear mechanisms.
- Measurement of the nonlinear properties of thin-film high- $T_c$  Josephson junctions in order to relate to films with defects
- Measurement of the linear and nonlinear microwave impedance in an applied dc magnetic field in order to understand the vortex pinning mechanisms
- Overall objective is better films for microwave components for application in communication and radar systems

## **STATUS OF EFFORT**

- Measurements of surface impedance in an applied dc magnetic field have been completed. A new model of pinning and the microwave losses associated with the pinning was developed. The model was corroborated by the analysis of the nonlinear data. This work was the subject of Nathan Belk's successfully completed Ph. D. thesis.
- Measurements of the microwave properties of fabricated Josephson junctions have been completed. Both edge junctions and grain-boundary junctions fabricated at NIST Boulder have been measured. Grain-boundary junctions should more closely agree with the plain films because low-angle grain boundaries may be responsible for the power dependence. This work was done with 24 degree bicrystal substrates. We also have begun characterization of junctions fabricated on substrates with smaller grain-

boundary angles, 10, 5, and 2 degrees that should more closely resemble the low-angle grain boundaries found in thin films. Joe Habib a Ph.D. student has conducted these measurements for his thesis.

- A new model of microwave impedance of long Josephson junctions has been developed to analyze the measurements. This was the topic of Capt. Christopher Lehner's MS thesis.
- In collaboration with Dr. Jeffery Herd of the Air Force Research Laboratory, we are continuing to develop a model of power dependence in high- $T_c$  films that includes an array of Josephson-junction-like defects. A Ph. D. student, Hao Xin is contributing to this effort
- Measurements of the power-dependent surface impedance of films continued in order to monitor improvements in film quality and to provide data for the modeling efforts.

## ACCOMPLISHMENTS/NEW FINDINGS

The research in microwave power handling of high- $T_c$  thin films has focused on three areas: 1. Nonlinear microwave flux dynamics, 2. Nonlinear impedance of engineered Josephson junctions and the dynamics of Josephson vortices associated with the nonlinear impedance, and 3. Extension of the coupled grain model to include a distribution of  $I_c$  and  $R_n$ .

### 1. Nonlinear microwave flux dynamics

We have carried out extensive measurements in a dc magnetic field. Our work has yielded an entirely new model of microwave-frequency vortex dynamics in thin films. Crucial to the development of this new model was the measurement of the surface impedance as a function of frequency as well as the characterization of the nonlinear properties. The measurement and the modeling are reported in two publications and were the subject of the thesis of Nathan Belk who finished his Ph. D. work in 1997. In essence, the model explains the linear as well as the nonlinear surface impedance by proposing that the microwave losses are dominated by thermally activated hopping of vortex segments between metastable pinning sites, and that a broad spectrum of pinning energies is found in the material. This differs substantially from the hitherto employed model of vortices pinned in parabolic wells that has been applied to the vortex dynamics of the low-temperature superconductors. This understanding of the microwave-frequency surface impedance in an applied field is essential for the development of microwave devices that operate in ambient magnetic fields. These results were reported in two publications.

### 2. Nonlinear impedance of engineered Josephson junctions

We have continued measurements of the microwave impedance of engineered Josephson junctions. Preliminary reports on these junctions are in two publications and a more detailed paper of results to date has been accepted for publication. In addition to the ramp-

type junctions initially studied, we have now characterized grain-boundary junctions grown on sapphire bicrystals at NIST Boulder. The grain-boundary junctions should better approximate the kinds of junctions that we believe are responsible for power dependence. In addition to the measurements, we have developed a model of the junctions that includes the unique boundary conditions experienced by the junctions in the stripline resonator. The model is a circuit simulation of the extended Josephson junction in the resonator that allows as input the exact microwave current distribution of the stripline. To solve the sine-Gordon equation, it uses a circuit model of many (of order 100) parallel, small, resistively shunted junctions coupled together by inductors to simulate the magnetic coupling by the Josephson penetration depth. The circuit model allows the introduction of the exact current distribution of the stripline resonator which is difficult to do otherwise. A significant portion of the modeling has been implemented by Capt. Christopher Lehner, a M.S. student who is on active duty with the U. S. Army.

These are the first direct measurements of the microwave properties of high- $T_c$  engineered junctions. Understanding the microwave nonlinear behavior of Josephson junctions is necessary to understanding the power dependence of thin films, since the defects are most likely to include grain boundaries and stoichiometric defects that behave like junctions. Knowledge of the microwave properties of the Josephson junctions is also of great importance for the application the junctions in microwave devices or high-speed digital circuits.

Furthermore and of equal importance, this effort has opened the study of a new wealth of physical phenomena, namely the dynamics of Josephson vortices. Youssef Habib who is in the final year of his Ph. D. research has been responsible for the experiments showing the dynamic effects. The measurements, and now modeling, show clear evidence of the generation and annihilation of Josephson vortices by the microwave currents flowing through the junction. This is the first evidence of vortex creation by microwave currents, although this mechanism has long been proposed to explain the observed power dependence.

### 3. Extension of the coupled grain model to include a distribution of $I_c$ and $R_n$ .

We have extended the coupled-grain model of plain films to include the effects of a distribution of  $I_c$  and  $R_n$  values each of which can be independently varied. In conjunction with this work we have emphasized the use of the so-called  $r$  value to characterize the nonlinearity of the film. The  $r$  value is the ratio of changes in surface resistance to surface reactance defined as  $r = \Delta R_s(H_{rf})/\Delta X_s(H_{rf})$ .

In addition to the distribution of junctions, the new modeling has included the small-junction properties as developed to fit our engineered-Josephson-junction measured results. This work has yielded results to explain experimental data of ours and others that could not be explained in any other way than by a distribution of junctions. In fact the extended coupled-grain model seems to be able to fit the entire range of surface impedance results that so far have been reported by us or by others. This implies that the

separation of the power dependence into two regions, a coupled-grain region at low power and a hysteretic region explained by the Bean model is not need to fit the data. The extended coupled-grain model is sufficient to explain the surface impedance over the entire range of microwave powers. A new Ph. D. student Hao Xin has contributed to this work.

## PERSONNEL SUPPORTED

- Dr. Daniel Oates Visiting Scientist and Lincoln Laboratory Staff
- Faculty: Professor Mildred Dresselhaus
- Graduate Students: Nathan Belk Ph. D. Student, Youssef Habib, Ph. D. Student, Hao Xin, Ph. D. Student, Capt. Christopher Lehner U. S. A., M. S. Student
- Dr. Gene Dresselhaus Research Staff

## Publications

D. E. Oates, Y. Habib, C. Lehner, J. Herd, R. Ono, and L. Vale, "Modeling the Nonlinear Surface Impedance of High- $T_c$  Thin Films," submitted to *Applied Superconductivity*.

Y. Habib, C. J. Lehner, D. E. Oates, L. R. Vale, R. H. Ono, G. Dresselhaus, and M. S. Dresselhaus, "Measurements and Modeling of the Microwave Impedance in High- $T_c$  Grain-Boundary Josephson Junction Fluxon Generation and rf Josephson-Vortex Dynamics," accepted in *Phys. Rev. B*. (1998)

D. E. Oates, Y. Habib, C. Lehner, and J. Herd, "Modeling the Nonlinear Surface Impedance of High- $T_c$  Thin Films," *Proceedings of the 6th International Superconductive Electronics Conference*, pp. 77-79, June 1997, Berlin Germany.

J. S. Herd, D. E. Oates, and J. Halbritter, "Identification and Modeling of Microwave Loss Mechanisms in  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ ," *IEEE Transactions on Applied Superconductivity* 7, pp. 1299-1302 (1997).

Y. Habib, D. E. Oates, G. Dresselhaus, and M. S. Dresselhaus, "Power Dependence of Microwave  $Z_s$  in High- $T_c$  Josephson Junctions: Measurements and Modeling," *IEEE Transactions on Applied Superconductivity* 7, pp. 2553-2557 (1997).

N. Belk, D. E. Oates, D. A. Feld, G. Dresselhaus, and M. S. Dresselhaus, "Linear and Nonlinear Microwave Dynamics of Vortices in  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  Thin Films," *Phys. Rev. B* 56, pp. 11966-11978 (1997).

J. McDonald, J. R. Clem, and D. E. Oates, "Critical-State Model for Harmonic Generation in a Superconducting Microwave Resonator," *Phys. Rev. B* 55, pp. 11823-11831 (1997).

T. C. L. G. Sollner, J. P. Sage and D. E. Oates, "Microwave Intermodulation Product and Excess Critical Current in  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  Josephson Junctions," *Appl. Phys. Lett.* **68**, 1003-1005 (1996).

N. Belk, D. E. Oates, D. A. Feld, G. Dresselhaus, and M. S. Dresselhaus, "Frequency And Temperature Dependence of  $Z_s$  of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  Thin Films In a dc Magnetic Field: Investigations Of Vortex Dynamics," *Phys. Rev. B* **53**, 3459-3470 (1996).

D. E. Oates, P. P. Nguyen, Y. Habib, G. Dresselhaus, M. S. Dresselhaus, G. Koren, and E. Polturak, "Microwave Power Dependence of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  Thin-Film Josephson Edge Junctions," *Appl. Phys. Lett.*, **68**, 705-707 (1996).

D. E. Oates, P. P. Nguyen, G. Dresselhaus, M. S. Dresselhaus, G. Koren, and E. Polturak, "Nonlinear Surface Impedance of YBCO Thin Films: Measurements Modeling and Effects in Devices," *Journal of Superconductivity*, **8**, 725-733 (1995).

G.-C. Liang, D. Zhang, C.-F. Shih, M. E. Johansson, R. S. Withers, W. Ruby, D. E. Oates, A. C. Anderson, P. A. Polakos, P. M. Mankiewich, E. DeObaldia, and R. E. Miller "High-Power HTS Microstrip Filters for Wireless Communication," *IEEE Transactions on Microwave Theory and Techniques*, **43**, 3020-3029 (1995).

P. P. Nguyen, D. E. Oates, G. Dresselhaus, M. S. Dresselhaus, and A. C. Anderson, "Microwave Hysteretic Losses in  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  and NbN Thin Films," *Phys. Rev. B*, **51**, 6686 (1995).

T. C. L. G Sollner, A. C. Anderson W. G. Lyons, D. E. Oates R. W. Ralston, J. P. Sage, P. A. Polakos, P. M. Mankiewich, E. DeObaldia, Z. Ma, and R. E. Miller, "High-Power YBCO Microwave Filters and Their Nonlinearities," to be published in *Proceedings of the 5th International Superconductive Electronics Conference September 1995 Nagoya Japan*.

G.-C. Liang, D. Zhang, C.-F. Shih, M. E. Johansson, R. S. Withers, D. E. Oates, and A. C. Anderson, "High-Power High-Temperature Superconducting Microstrip Filters for Cellular Base-Station Applications," *IEEE Transactions on Applied Superconductivity*, **5** pp. 2652-2655 (1995).

G.-C. Liang, C. F. Shih, D. Zhang, R. S. Withers, and D. E. Oates, "High Power HTS microstrip Filters for Wireless Communications," *1994 MTT-S Digest*, pp. 183-186, 1994.

S. Revenaz, D. E. Oates, D. Labbe-Lavigne, G. Dresselhaus, and M. S. Dresselhaus, "Frequency Dependence of  $Z_s$  of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$  Thin Films in a dc Magnetic Field: Investigation of Vortex Dynamics," *Phys. Rev. B*, **50**, pp. 1178-1189 (1994).

## Invited Conference Papers

“High-Power Microwave Devices: How Far Can Thin Films Go?”

D. E. Oates and A. C. Anderson,  
Spring MRS Meeting San Francisco CA, April 1995.

“Fabricated Josephson Junctions, Coupled-Grain And Bean Models”

D. E. Oates, J. S. Herd, J. Halbritter, and Y. M. Habib  
Fourth Symposium on High-Temperature Superconductors in High-Frequency Fields,  
Sept. 29-Oct 2, 1996 Pacific Grove CA.

“Modeling the Nonlinear Surface Impedance of High- $T_c$  Thin Films,”

D. E. Oates, Y. Habib, C. Lehner, and J. Herd,  
6th International Superconductive Electronics Conference June, 25-28, 1997, Berlin  
Germany.

## Contributed Conference Papers and Posters

“Microwave Power Dependence of  $\text{YBa}_2\text{Cu}_3\text{O}_{7.8}$  Thin Film Josephson Edge Junctions” .D.

E. Oates, P. P. Nguyen, Y. Habib, G. Dresselhaus, M. S. Dresselhaus, G. Koren, and E.  
Polturak,  
APS San Jose CA, Talk March Meeting 1995.

“Analysis of Frequency Dependence of Vortex Dynamics in  $\text{YBa}_2\text{Cu}_3\text{O}_{7.8}$  Thin Films in a  
DC Magnetic Field”

Nathan Belk, D. E. Oates, D. A. Feld, G. Dresselhaus, and M. S. Dresselhaus,  
APS San Jose CA, Talk March Meeting 1995

“DC Magnetic Field Effects on the Microwave Power

Dependence of  $\text{YBa}_2\text{Cu}_3\text{O}_{7.8}$  Thin Film Josephson Edge Junctions,”  
Y. M. Habib, D. E. Oates, G. Dresselhaus, and M. S. Dresselhaus,  
Fall MRS, Boston, Poster December 1995.

“Analysis of Frequency Dependence of Vortex Dynamics in  $\text{YBa}_2\text{Cu}_3\text{O}_{7.8}$  Thin Films in a  
DC Magnetic Field,”

Nathan Belk, D. E. Oates, D. A. Feld, G. Dresselhaus, and M. S. Dresselhaus, MRS Fall  
Boston, Poster December 1995.

“Nonlinear Microwave Flux Dynamics: Role of Pinning and Power Dependence,”

Nathan Belk, D. E. Oates, M. S. Dresselhaus, and G. Dresselhaus  
APS March Meeting, St. Louis, Talk 1996

“Nonlinear Microwave Flux Dynamics: Relationship between Pinning and Power  
Dependence,”



D. E. Oates, Nathan Belk, G. Dresselhaus, and M. S. Dresselhaus  
MRS Abstracts, page 308 (1996). MRS, San Francisco, Talk

"Identification and Modeling of Microwave Loss Mechanisms in  $\text{YBa}_2\text{Cu}_3\text{O}_{7.8}$  thin films."  
J. S. Herd, D. E. Oates, and J. Halbritter,  
1996 Applied Superconductivity Conference, Pittsburgh, Talk.

"Power dependence of microwave  $Z_s$  in high- $T_c$  Josephson junctions: measurements and modeling."  
Y. M. Habib, D. E. Oates, G. Dresselhaus, and M. S. Dresselhaus,  
1996 Applied Superconductivity Conference, Pittsburgh, Poster

"Vortex dynamics in YBCO thin-film Josephson Edge Junctions: Mechanisms for nonlinear Microwave and dc Power Dependence,"  
Y. Habib, D. E. Oates, C. Lehner, G. Dresselhaus, and M. S. Dresselhaus  
Materials Research Society Fall Meeting Dec. 2-6, 1996 Boston MA

"Linear and nonlinear microwave dynamics of vortices in  $\text{YBa}_2\text{Cu}_3\text{O}_{7.8}$  thin films,"  
N. Belk, D. E. Oates, D. A. Feld, G. Dresselhaus, and M. S. Dresselhaus  
APS March meeting March 1997 Kansas City MO

"Microwave Power Dependence in YBCO Josephson Junctions: rf Josephson Fluxon Generation,"  
Y. M. Habib, D. E. Oates, C. J. Lehner, G. Dresselhaus, and M. S. Dresselhaus  
APS March meeting March 1997 Kansas City MO

"Vortex dynamics in YBCO thin-film Josephson Edge Junctions: Mechanisms for nonlinear Microwave and dc Power Dependence,"  
Y. Habib, C. Lehner, D. E. Oates, G. Dresselhaus, and M. S. Dresselhaus  
Poster presented at NATO Summer school, Norway June 1997.

Measurements and Modeling of the Microwave Impedance in High- $T_c$  Grain Boundary Josephson Junctions: Josephson Fluxon Generation and Vortex Dynamics,"  
Y. Habib, D. E. Oates, C. Lehner, R. Ono L. Vale, G. Dresselhaus, and M. S. Dresselhaus  
Materials Research Society Fall Meeting Dec. 1997 Boston MA